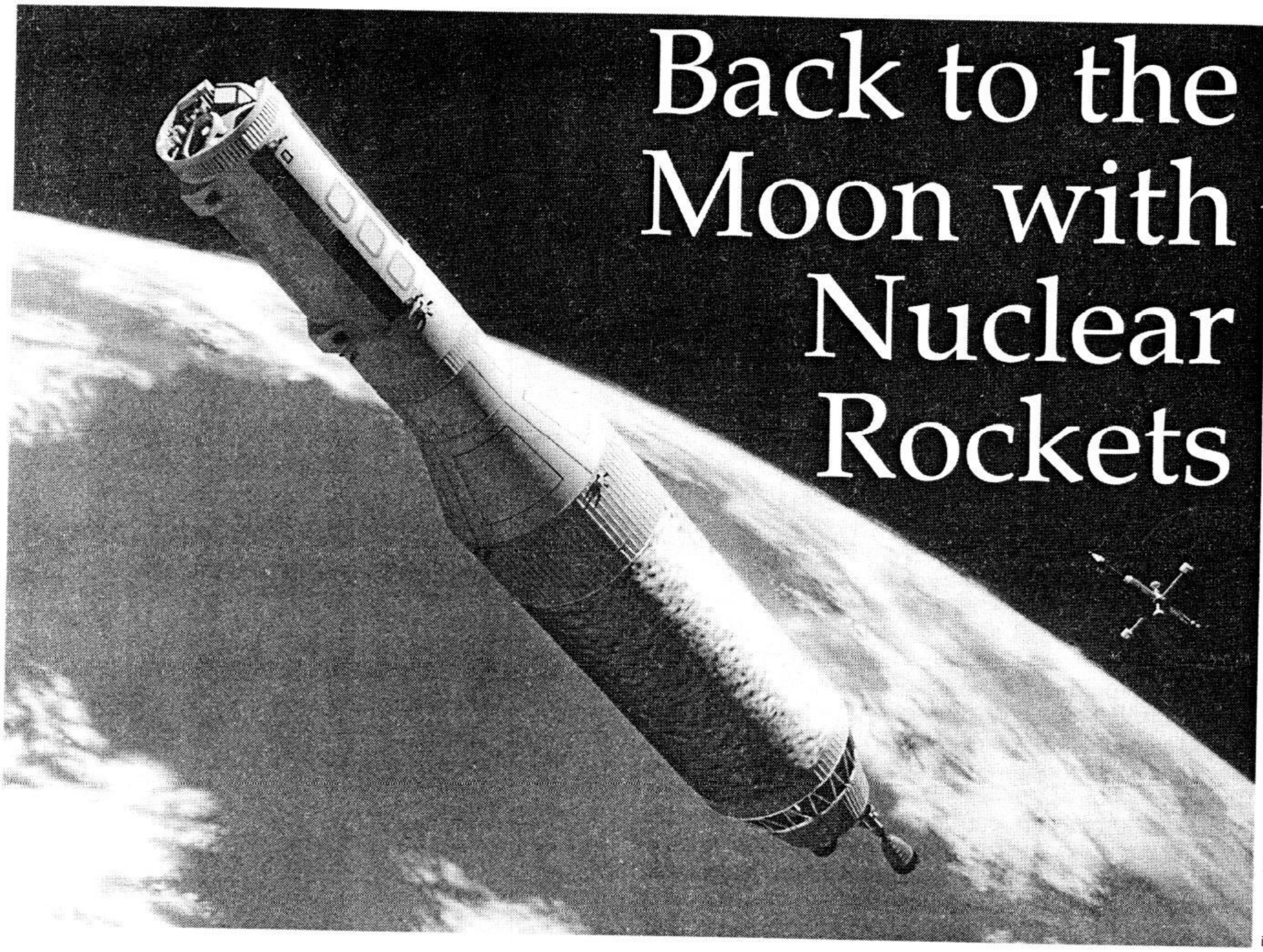
Back to the Moon with Nuclear Rockets



Figures and illustrations are courtesy of Dr. Stanley Borowski/NASA

by Marsha Freeman

A Moon shuttle trip will be only a 24-hour commute—if we go nuclear.

Thirty years ago, on July 20, 1969, the first Apollo astronauts landed on the Moon, within the timeframe President John F. Kennedy had proposed eight years earlier, of a lunar landing before the end of the 1960s. To achieve this goal, the National Aeronautics and Space Administration (NASA) pushed to the limit the propulsion technology that had been under development before World War II, and created the massive Saturn V rocket, using chemical combustion as the mode of force.

Today, the International Space Station is under construction in Earth-orbit, soon to provide mankind with a multipurpose research and development facility, which can function, scientifically and physically, as a jumping-off point to more distant venues. With the International Space Station soon to be available, space planners are now considering what the space exploration programs for the 21st century should be.

There are some who have chosen to look back, rather than forward, having succumbed to the demoralization of the past 30 years since the end of the Apollo program. Mars Society founder, Dr. Robert Zubrin, for example, is convinced that there will be no return to the central planning of visionary space missions that existed in the 1960s. Asserting that the American people are "bored" with the Moon ("been there, done that"), Zubrin has proposed a series of gimmicks to entice congressional support for a "more sexy" manned Mars approach, whose main selling point is that it will be quick and cheap.

Such an approach assumes the availability and use of Apollo-era hardware; Zubrin insists that the old Saturn V rocket could be resurrected. Aside from the fact that today Saturn V rockets exist only in museums, and it is estimated that it would take 10 years and $10 billion to recreate them, even President Kennedy,

A Liquid-Oxygen Augmented Nuclear Thermal Rocket-powered transfer stage leaves Earth orbit, carrying a passenger transport module on a 24-hour trip to the Moon. In the background is the Earth-orbital International Space Station.

in 1961, did not believe that chemical propulsion systems were the future of the U.S. space program. Speaking on May 25, 1961, in his "Special Message to the Congress on Urgent National Needs," Kennedy outlined his lunar program and then requested "an additional $23 million, together with the $7 million already available, to accelerate development of the Rover nuclear rocket." The President stated:

> This gives promise of someday providing a means for even more exciting and ambitious exploration of space, perhaps beyond the Moon, perhaps to the very end of the solar system itself.

Between 1959 and 1972, the United States made what in today's dollars would be a $10 billion investment to design, develop, and test the world's first space nuclear reactors. Although very successful, the space nuclear propulsion program carried out by NASA and the Atomic Energy Commission was terminated in early 1973, when failed economic policies led to savage cuts in NASA's budget, removing lunar colonization and manned missions to Mars from the nation's space agenda.

Today, the time is near when we should go back to the Moon—but we should not go the way we did 30 years ago. We should push forward on the frontiers, creating the enabling technologies not only to travel to the Moon, but to live and work there. Only this will lay the basis for manned missions to Mars.

Why Nuclear?

The move from chemical energy to nuclear power will be a quantum leap advance in space propulsion, similar to the advances that occurred when mankind moved from foot power and unpowered water transport, to horse power, the internal combustion engine, and, finally, to jet power and electric propulsion: We will be able to go farther, go faster, and carry more cargo.

Travel in space, as anywhere else, requires large amounts of energy. Today's rockets use the energy liberated from the burning of chemical fuels to provide the thrust to move into space. But the density of the energy released from a nuclear fission, or nuclear fusion, reaction is orders of magnitude

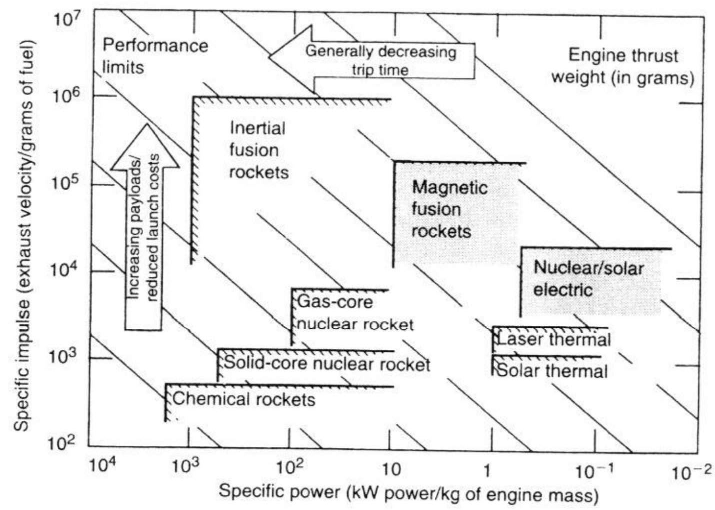


Figure 1
SPECIFIC IMPULSE AND POWER: COMPARING PERFORMANCE OF PROPULSION TECHNOLOGIES
The improved performance of the near-term solid-core nuclear thermal reactor over chemical propulsion is seen in this comparison of specific impulse and power parameters for various technologies, and the directions needed for the future.

Figures and illustrations are courtesy of Dr. Stanley Borowski/NASA

Space Propulsion Parameters

There is more to space propulsion efficiency than simply the raw energy that is produced. One of the key performance parameters of a propulsion system is the *specific impulse,* which provides a measure of the efficiency of the thrust produced by an engine, for a given amount of propellant used, per second. Specific impulse is dependent upon the velocity of the mass produced as exhaust. The specific impulse of the Space Shuttle liquid hydrogen/liquid oxygen engines is about 450 seconds. Systems using onboard electric power, solar energy, or beamed laser power for propulsion can reach specific impulse measurements between 1,000 and 10,000 seconds.

But high specific impulse alone does not make a propulsion system. The *thrust* that is produced by any propulsion system is the product of both the propellant velocity and the mass flow rate of the exhaust. In the main engines of the Space Shuttle orbiters, a large thrust is obtained by using a large amount of propellant (high mass flow rates), which is expelled at a relatively low velocity, approximately 4,500 meters per second, through a chemical reaction.

Using nuclear fission, it is possible to obtain high thrust by expelling a relatively small amount of mass, at very high velocity, up to 10,000 meters per second.

In addition to specific impulse (the efficiency of the fuel), and thrust (the total "push" power of the system), the engine should be designed so that the *thrust-to-weight ratio* allows acceleration levels appropriate for different missions. The thrust-to-weight ratio describes the number of pounds of force per pound of engine weight.

Colonizing space necessitates families of new launch vehicles. Propulsion systems for manned spaceflight should be optimized to move people as expeditiously as possible, which requires a trade-off with the amount of freight tonnage that can be aboard. Cargo vehicles should be optimized to move as much freight as possible, and can travel more slowly.

higher. Dr. Stanley Borowski from NASA's Lewis Research Center (which was recently renamed for former Senator and astronaut John Glenn), points out that an equivalent amount of energy would be released from 13 tons of liquid hydrogen and oxygen, 2.0 grams of uranium, .5 gram of deuterium (as a fusion fuel), and .02 grams of equal parts of hydrogen and antihydrogen (See table, p. 59, and Figure 1).

In reality, the only advantage to using chemical propulsion systems today, is that we know how.

With the goal of maximizing the parameters for propulsion engine efficiency using nuclear energy, teams of scientists and engineers, both in the United States and in Russia, have been designing ingenious new systems for manned and cargo vehicles. It would be inefficient (and backwards) to plan to move mankind into space using the chemical propulsion systems of the Apollo era. We will need to take many more than three people per trip, and many tons more of supplies than those for a few-day stay.

Using nuclear energy technology in space is not an untested concept. During the space nuclear program of the 1960s, NASA designed, built, and tested 20 rocket reactors. The Rover and NERVA (Nuclear Engine for Rocket Vehicle Application) programs demonstrated the feasibility of space nuclear power, testing a wide range of engine sizes, using liquid hydrogen as both the coolant for the reactor, and the propellant, expelled to create thrust.

A few years after the start of the nuclear rocket program in the United States, a similar effort was initiated in the former Soviet Union. Although there were no integrated engine system tests conducted, nuclear and non-nuclear subsystems tests, including fuel element and reactor tests, were conducted at the Semipalatinsk facility in Kazakhstan. High-temperature fuel elements made of carbide composites were developed, capable of producing hydrogen exhaust temperatures higher than 3,000 K, or about 500 degrees more than the best NERVA fuel elements.

Ten years ago, during the celebration for the 20th anniversary of the first lunar landing, President George Bush announced that NASA should be looking toward a return to the Moon, and sending men on to Mars. NASA's Office of Exploration began investigating various technology options for reaching these goals.

A New Generation Nuclear Thermal Rocket

In 1992, NASA's Nuclear Propulsion Office at the Lewis Research Center in Ohio funded a joint program with the experts in the United States and the former-Soviet nations to design a small, advanced Nuclear Thermal Rocket (NTR) engine (Figure 2). The team included experts from Aerojet, the U.S. nuclear supplier Babcock & Wilcox, and a Commonwealth of Independent States (CIS) consortium, Energopool. In September of that year, a U.S. team visited test facilities in Kazakhstan and met with their CIS counterparts to conduct detailed studies of the CIS space nuclear reactor concept.

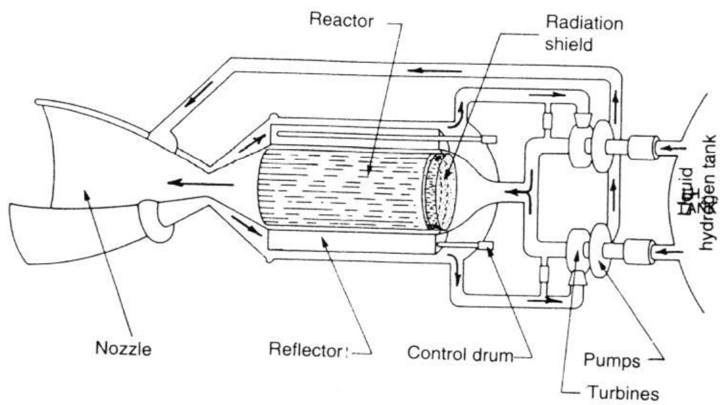


Figure 2
SCHEMATIC OF SOLID-CORE NUCLEAR THERMAL ROCKET
The heart of the solid-core nuclear thermal rocket design is shown here. Cryogenic liquid hydrogen is pumped from storage tanks (right) past the radiator to cool it. The pre-heated hydrogen is then fed through the nuclear fission reactor, heated to about 3,000 K, and expelled through the nozzle, creating the thrust for the engine.

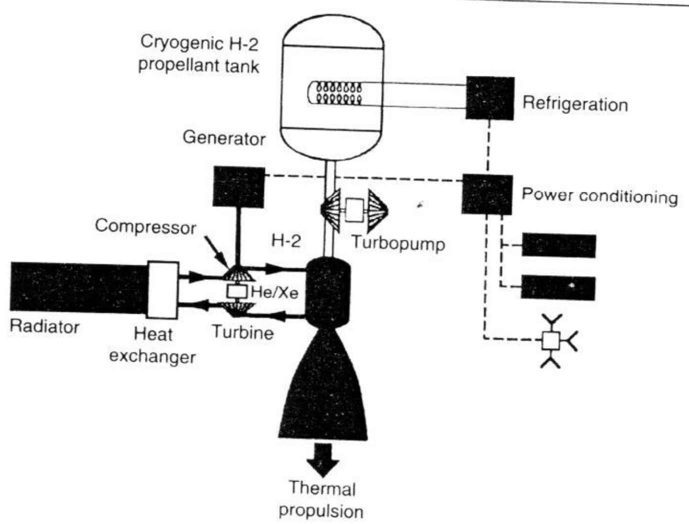


Figure 3
MOVING TO A 'BIMODAL' NUCLEAR THERMAL REACTOR STAGE
Dr. Borowski and his colleagues have proposed that the solid-core reactor used for propulsion also supply the electricity needed on board the spacecraft for life support, in the case of manned vehicles, as well as for powering the communications, electronics, and computer systems. It can also run the refrigeration system that maintains cryogenic temperatures to keep the hydrogen propellant in liquid form.

Shown here is a design for a closed Brayton cycle energy conversion system that uses the high-temperature gas from the reactor to turn a turbine and produce electric power.

This joint study came up with advanced fuel designs, such as "twisted ribbon" fuel elements, which could be adjusted according to the desired exhaust temperature. The proposed engine was designed for a specific impulse of 940 to 960 seconds, about double that of today's advanced liquid hydrogen chemical engines. Reactor tests at Semipalatinsk demonstrated hydrogen propellant exhaust temperatures of 3,100 K for more than 1 hour, and 2,000 K for 2,000 hours.

In 1993, the U.S. participants in the program suggested that a joint effort would bring significant benefits to all the countries involved. Using the existing CIS test facilities would mean that the United States would not have to spend time and resources to duplicate them. The economic situation of the Russian and other CIS scientists and engineers would be improved, and their expertise put to good use. By the end of the Bush administration, however, it was clear that neither the White House nor the Congress was willing to *pay* for any visionary manned space program, and the nuclear propulsion research was again put on a back burner.

Despite this situation, a team of experts led by Dr. Stanley Borowski from NASA Lewis Research Center, wanted to ensure that when the nation made the decision to go back to the Moon, nuclear propulsion would be seriously considered, because it is far superior to chemical propulsion or to various low-thrust options that are less attractive for manned space travel. Over the past five years, Borowski's team has greatly extended the capabilities of the CIS Nuclear Thermal Rocket design.

Every spacecraft in operation today, whether manned or not, requires an on-board electricity supply to power the electronics, computers, and scientific instruments for the mission. In the case of the Space Shuttle, chemical fuel cells provide this energy, which is required not only for spacecraft operations but also for life support. Spacecraft with longer mission times in Earth orbit, such as the Russian Mir space station, the International Space Station, commercial communications and other satellites, and near-Earth scientific satellites carry large solar arrays that convert solar energy into electricity.

Outer Solar System robotic space probes, such as the Galileo spacecraft which is orbiting Jupiter, or the Cassini spacecraft on its way to Saturn, carry a few pounds of radioactive isotopes which produce heat as they decay, and this energy can be converted to very small amounts of electricity, adequate to power the instruments on board. But if nuclear energy is used as the propulsion system of tomorrow's lunar vehicles, a ready supply of electricity for use on board can be produced from the same reactor that is powering the engines.

Borowski suggests that the nuclear-powered submarine, in which the reactor heat produces high-pressure steam to drive turbines for the ships propeller and turbines that produce all of the ship's electricity, is a good model for extending the duty of the nuclear reactor on a

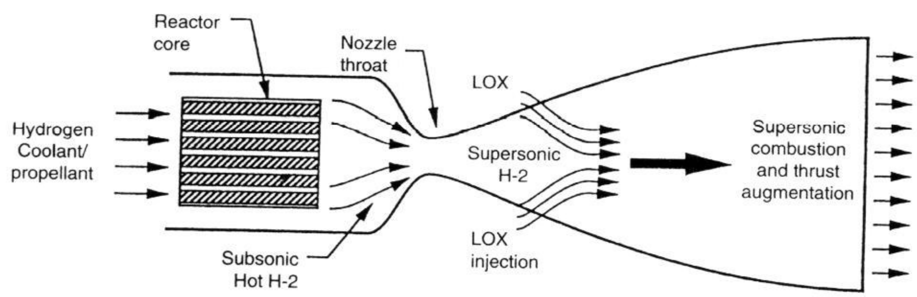


Figure 4
AUGMENTING THE NUCLEAR ENGINE WITH OXYGEN
The Borowski team has also developed a "trimodal" design for the nuclear thermal rocket, which introduces liquid oxygen (LOX) into the flow stream of the supersonic hydrogen exiting the nozzle, to increase the thrust and flexibility of the engine. The hydrogen and oxygen combust spontaneously.

THE TRADE-OFF BETWEEN THRUST AND SPECIFIC IMPULSE

	Specific impulse (seconds)				
Life (hours) Temperature (K)	5 2,900	10 2,800	35 2,600	Tankage fraction (%)	Thrust/weight ratio
Oxygen/ hydrogen ratio					
0.0	941	925	891	14.0	3.0
1.0	772	762	741	7.4	4.8
3.0	647	642	631	4.1	8.2
5.0	576	573	566	3.0	11.0
7.0	514	512	508	2.5	13.1

In the liquid-oxygen-augmented nuclear thermal rocket design, an increasing amount of oxygen added to the lighter hydrogen exhaust stream will increase the thrust of the engine, by increasing the mass of the exhaust. At the same time, however, it reduces the specific impulse of the system, by slowing down the exhaust.

The table demonstrates that while the specific impulse decreases by about 45 percent, from about 940 to 515 seconds, if the ratio of oxygen/hydrogen is 7.0, the engine thrust-to-weight ratio increases by nearly 440 percent. This increased thrust through oxygen augmentation, Dr. Borowski states, means that "big engine" performance can be obtained with small nuclear engines.

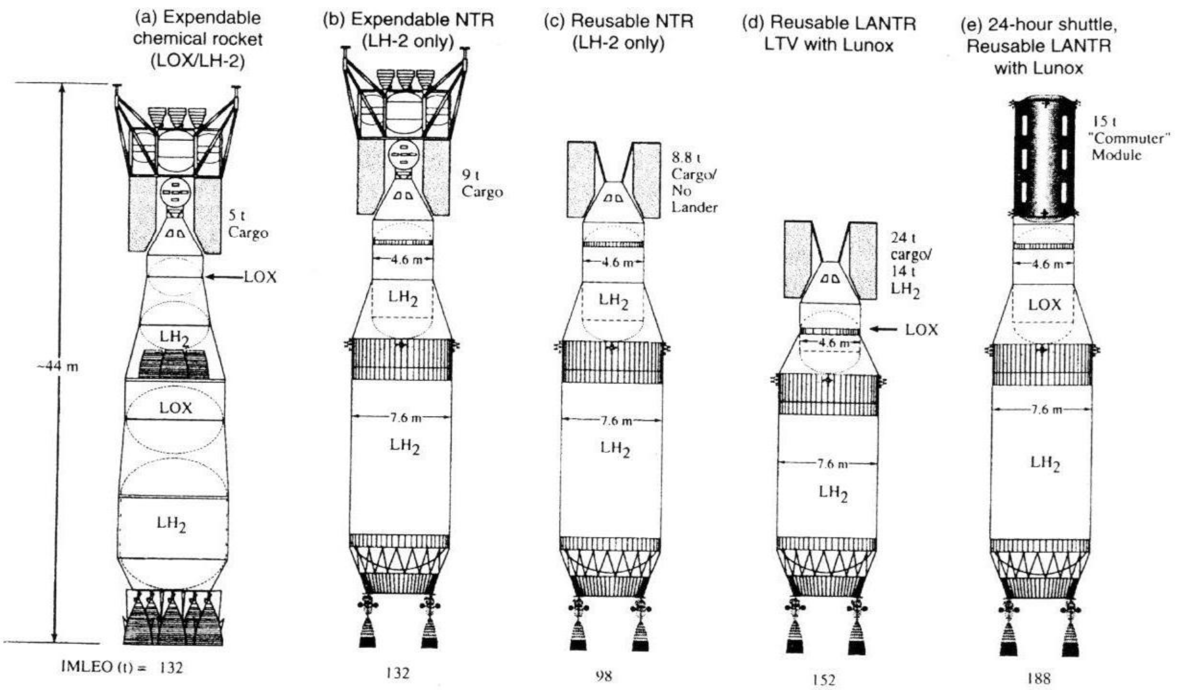


Figure 5
RELATIVE SIZE AND MASS FOR CHEMICAL AND NUCLEAR VEHICLES

An Apollo-style chemical rocket, able to land five tons of cargo on the surface of the Moon is shown in (a). Vehicle (b), with the same 132 tons of initial mass in low-Earth-orbit, substitutes a Nuclear Thermal Rocket (NTR), also expendable, for the chemical combustion, increasing payload to the surface by 80 percent, to 9 tons.

If the NTR is reusable, and lunar oxygen is available, as in (c), there is no need for a lander to be transported on each mission from Earth, because it will be refueled on the lunar surface and make round trips between the surface and lunar orbit. Nearly 9 tons of cargo could be delivered with this design.

If liquid oxygen is added to the propulsion system, in the LANTR design (d), then 24 tons of cargo can be carried to the Moon, in addition to 14 tons of terrestrial hydrogen, needed for the chemical propulsion systems of the lunar vehicles. If hydrogen were to be extracted from the ice at the lunar poles, more cargo could be carried instead.

Rockets (a)-(d) are all 84-hour vehicles. Shown in (e) is a 24-hour lunar shuttle design, where the LANTR propulsion system and lunar oxygen are in use. Payload capability is 15 tons, with increased thrust used to decrease the trip time, making possible one-day trips to the Moon.

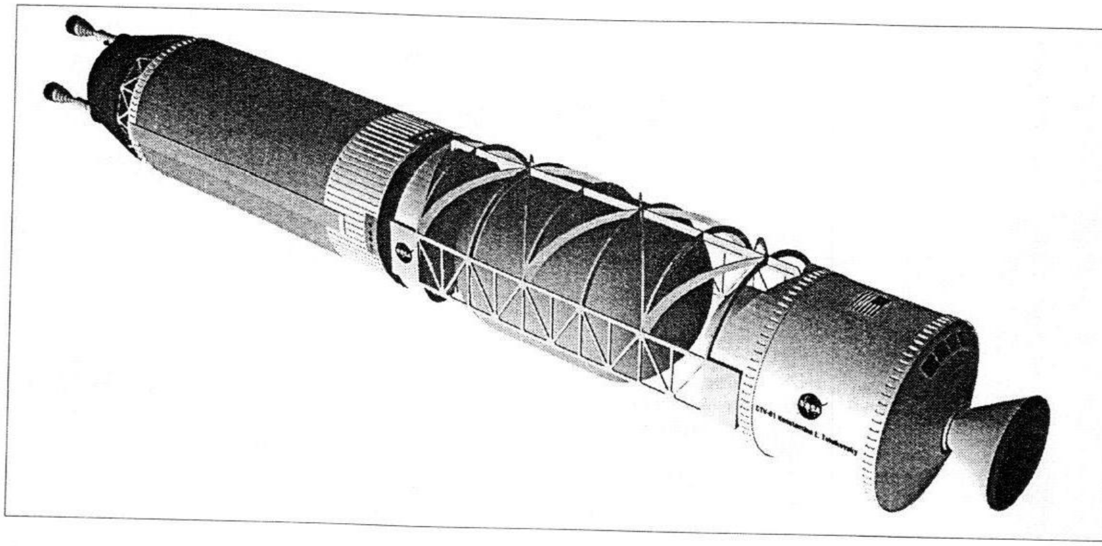
spacecraft. Bimodal operation of a solid core Nuclear Thermal Rocket is possible, producing both propulsive force and electricity, because the rocket contains substantially more fuel in its core than it consumes in its propulsion mode (Figure 3). The engine can be reconfigured, according to Borowski, so that substantial electrical power can be generated for the on-board spacecraft systems, including the active refrigeration of liquid hydrogen propellant, life support, and high data rate communications with Earth, obviating the need for a separate electric-generating system.

Quadrupling Payload with Lunar Oxygen

While examining ways to increase the efficiency of nuclear propulsion, and take advantage of an array of techniques that might be combined, Borowski and his colleagues developed the innovative "trimodal" Nuclear Thermal Rocket concept. In addition to providing the energy for the primary propulsion system, and on-board electrical power for the spacecraft, they propose augmenting engine thrust using a supersonic oxygen afterburner nozzle.

In this configuration, liquid oxygen would be injected into the bell-shaped section of the engine, where the hydrogen propellant has been accelerated to supersonic speeds. After injection, the low-mass, high-velocity hydrogen and the higher-mass oxygen would burn spontaneously, adding both mass and chemical energy to the rocket exhaust to increase thrust. The substitution of high-density liquid oxygen in place of lower-density liquid hydrogen increases the mass flow, and also reduces the mass and tank volume required for the propellant, leading to smaller space vehicles. Borowski describes this as "scramjet propulsion in reverse." In a scramjet, the engine takes in air for combustion from the atmosphere when the aircraft is flying at supersonic speeds.

In addition to increasing thrust and reducing vehicle size, the Liquid-Oxygen Augmented Nuclear Thermal Rocket (LANTR) introduces additional flexibility to the operation of



Three-dimensional view of the Bimodal Nuclear Thermal Rocket, with the Earth Return Crew Vehicle attached.

the entire system (Figure 4 and table). By varying the ratio of oxygen-to-hydrogen in the engine, it can operate over a wide range of thrust and specific impulse values, without changing the operating characteristics or power output of the nuclear reactor. For example, as the mixing ratio of oxygen to hydrogen increases from 0 to 7, the engine thrust-to-weight ratio increases by about 400 percent, while the penalty in reduced specific impulse is only about 45 percent.

The higher thrust values translate into shorter burn times for the nuclear engine to impart a required velocity, which extends the lifetime of the engine itself.

The flexibility introduced by this liquid oxygen augmentation allows the same basic propulsion system to be used among a family of vehicles with a variety of mission goals. The next quantum leap would be to avoid carrying the oxygen from Earth along in the spacecraft, but, like the scramjet, to be able to find it on the fly.

The Lunar Filling Station

There is little doubt that the first lunar resource that will be exploited for operational purposes will be oxygen, which makes up nearly half the mass of the Moon. A number of different processes have been under development through government and industrial efforts for efficient extraction of lunar oxygen from the soil, or regolith,[1] generally conceived to be used as the oxidant for chemical propulsion systems. But lunar-derived oxygen can also dramatically improve the capabilities of the liquid-oxygen augmented Nuclear Thermal Rocket (LANTR) system. Any use of "local" resources on the Moon increases the payload capability of the transport system, which does not have to carry all of its consumables from Earth.

In the plan by Borowski et al., the use of nuclear propulsion technology would be evolutionary, starting with an unaugmented, expendable Nuclear Thermal Rocket system (Figure 5). This would maximize the payload delivery to the surface, while minimizing the initial mass that must be launched from the Earth's surface to orbit. Because of the doubling of specific impulse using nuclear thermal, rather than chemical propulsion technology, the amount of payload that can be delivered to the lunar surface is 80 percent larger than that of chemical systems, for the same initial mass in low-Earth-orbit. This will translate directly into the reduced amount of time necessary for establishing advanced resource development, manufacturing, and living facilities on the Moon. The increased payload capability of the nuclear transport vehicles will allow the delivery of modular lunar oxygen production facilities to the surface of the Moon.

The first use of lunar oxygen would be to fuel the lunar landing vehicles, which will make the round trip from the surface of the Moon to the lunar transportation vehicle in lunar orbit. This will reduce the amount of liquid oxygen that must be carried from Earth orbit. As lunar-derived oxygen became readily available, reusable oxygen-augmented nuclear engines would come on line, increasing the payload throughput of the entire system. Borowski and his team estimate that with a reusable nuclear lunar transport vehicle, 400 percent more payload could be delivered on each round trip mission.

Judging from the results so far from the Lunar Prospector orbital mission, there is also the possibility of exploiting the deposits of water ice at the Moon's poles, to procure the liquid hydrogen needed as a reactor coolant and exhaust propellant for the nuclear propulsion engines.

Once the liquid-oxygen augmented "reverse scramjet" system were added, the effective specific impulse of the engine can be potentially *doubled again* to 1,500 to 2,000 seconds, or three to four times the efficiency of chemical propulsion systems. In order to deliver an equivalent amount of cargo to the Moon, a chemical propulsion system would have to deliver three times as much mass to low-Earth orbit. Specific impulse parameters at this level previously had been projected only for advanced second-generation gaseous core nuclear reactor systems; however, with the LANTR, they can be obtained using the near-term solid core nuclear technology and *in situ* propellant technologies that have already been developed and demonstrated here on Earth.

The 24-Hour Trip to the Moon

The objective of the LANTR program that Borowski has designed is to "grow" an initial lunar outpost into "permanent settlements staffed by visiting scientists and engineers representing both government and private commercial ventures."

The liquid-oxygen-augmented nuclear engine can enable 24-hour "commuter" shuttle trips to the Moon, or about what it takes to fly today from the East Coast of the United States to Asia. Exposing travelers to the radiation environment of space for as little time as possible should be one criterion in evaluating any particular propulsion system.

This nuclear lunar shuttle spacecraft would start its journey in Earth-orbit, where it would fill up with liquid hydrogen and liquid oxygen at a propellant depot. The total engine burn time for the high-velocity quick transit to the Moon is just under 47 minutes. Because the engine is designed for a 34.5 hour lifetime, the liquid-oxygen-augmented nuclear engine could make about 44 round trip missions to the Moon.

The trip, as envisioned in the LANTR program, would start with a ride on the Space Shuttle or similar future vehicle, to the Earth-orbital International Space Station. There, passengers would enter their transport module, to be brought to low-Earth-orbit inside the Space Shuttle. The passenger transport module provides the "brains" for the nuclear shuttle vehicle, and life support for the 18 passengers and two crew members during their 24-hour journey.

After leaving the space station, the passenger transport module would dock with the nuclear shuttle, which would be waiting a distance away. Acceleration levels experienced by the crew and passengers during Earth departure and translunar injection would range from less than one-quarter Earth's gravity, to perhaps one-half.

After the 24-hour trip to lunar orbit, the passenger module would separate from the nuclear shuttle, and dock with a lunar landing vehicle, which would be waiting in lunar orbit. A propellant depot in lunar orbit would refuel the nuclear shuttle for its trip back to Earth orbit. The fuel depot would also provide the lunar landing vehicle with liquid hydrogen brought from Earth (assuming hydrogen from the ice on the Moon is not used), which is needed in its chemical propulsion system to deliver the passenger transport module to the lunar surface. After landing on the surface, the passenger transport module would be placed on a "flatbed" surface vehicle for transport to the lunar settlement.

Dr. Borowski has estimated that a small advanced Nuclear Thermal Rocket engine could be developed, ground tested, and readied for flight in about seven years, at a cost of about $1.5 billion. It would be the building block for a multi-engine lunar transport vehicle, later to be augmented with oxygen combustion, and eventually, to use oxygen mined on the Moon. After a tryout period, in which the relatively short-distance trips to the Moon would become routine, the Nuclear Thermal Rocket system will be ready for a much more demanding task—manned missions to Mars.

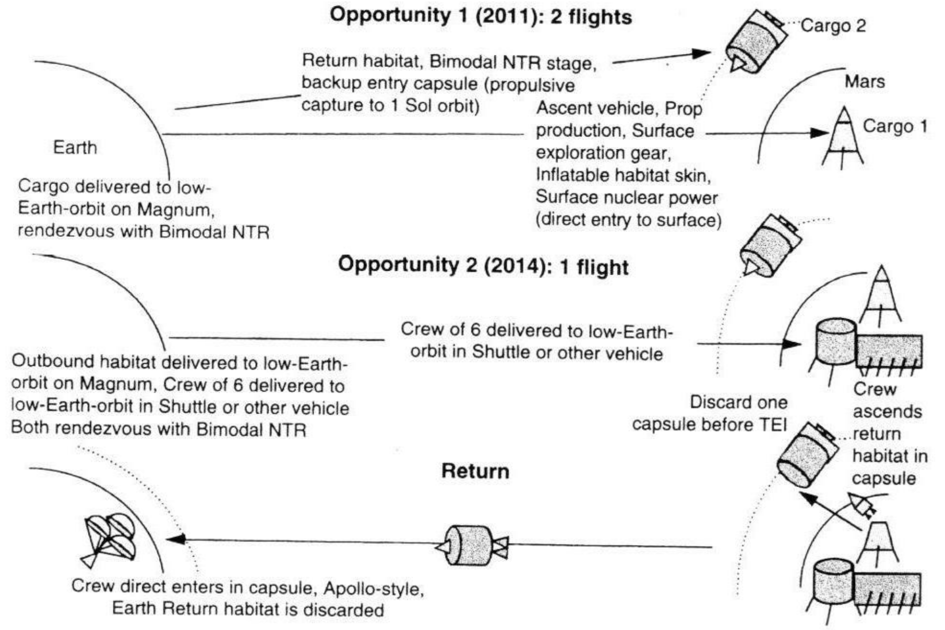


Figure 6
GOING TO MARS WITH NUCLEAR PROPULSION
NASA is studying various scenarios for manned missions to Mars in the second decade of the next century. All of the studies assume that there will be a heavy-lift "Magnum" booster available, with a payload capacity of about 80 tons, to low-Earth-orbit, and that the missions will be split between cargo flights and piloted flights. Using nuclear propulsion systems can reduce the transit time to Mars, or increase the tonnage of payload that can be transported, as compared to chemical propulsion systems.

A Family of Nuclear Vehicles for Mars

In a technical memorandum published at the end of last year,[2] Drs. Borowski and Leonard Dudzinski from NASA Lewis, and Melissa McGuire from Analex Corporation, presented a comprehensive plan for how to accomplish the goals of a Design Reference Mission to Mars that has been promulgated by NASA, using nuclear thermal rather than chemical propulsion.

One NASA Design Reference Mission considers the use of an expendable trans-Mars injection stage powered by Nuclear Thermal Rocket engines. But Borowski et al. propose that the disposal of the NTR engine after a single use is a "costly and inefficient use of this high performance stage." Instead, they propose a "family of modular 'bimodal' Nuclear Thermal Rocket vehicles," which use a common "core stage," powered by three 15,000-pound thrust engines based on the CIS design (Figure 6). These would also produce 50kW of electrical power

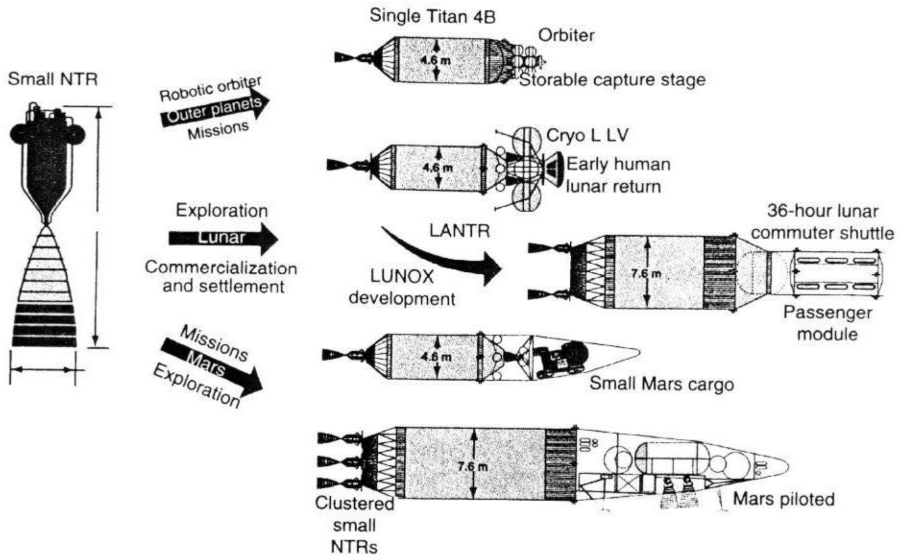


Figure 7
NUCLEAR POWER TO OPEN THE SOLAR SYSTEM
The basic small Nuclear Thermal Rocket engine will provide a versatile capability for a variety of missions. It will enable the exploration, settlement, and commercial development of the Moon, and clusters of small nuclear engines can carry men and material to Mars. In addition, unmanned robotic exploration missions to the outer planets, will benefit from the stand-alone capabilities of nuclear propulsion.

for crew life support and other requirements aboard the spaceship. Some of the advantages in this mission design are that fewer different transportation system elements are required, the initial mass in low-Earth orbit is reduced, and space operations are simplified.

Currently, NASA's Mars Exploration Study Team is assessing a variety of mission architectures and transportation options for conducting a manned mission to Mars in the timeframe of year 2014. In general outline, the proposal is centered on split cargo-piloted missions, and *in situ* production of propellant on Mars's surface. Two cargo missions would launch in November 2011, preceding the manned launch in 2014.

Borowski's team at NASA Lewis has developed an "all NTR" Mars mission option, based on using standardized engine and other components (Figure 7). Safety and flexibility are enhanced with this modular approach, vehicle design and assembly are simplified, and costs are reduced.

The first step in the manned mission is to deliver the common-core stage of the Nuclear Thermal Rocket to low-Earth-orbit on an 80-ton payload launch vehicle, dubbed "Magnum," which has been proposed by NASA for its studies. Approximately 30 days later, a second Magnum launch will deliver a structural truss, propellant tank, habitat module, and consumables to low-Earth-orbit, where rendezvous and docking with the core stage takes place. A reusable Shuttle or similar vehicle will then deliver the crew.

Because the nuclear-core stage has a higher performance capability than comparable chemical propulsion systems, it will be possible to decrease the risk of the mission to the crew, by carrying along a second, back-up Earth-return capsule. The first one would have been delivered in a preceding unmanned cargo mission. If the crew, for any reason, cannot land on Mars to retrieve the first return capsule, in this plan, they would have the spare return capsule available.

The bimodal nuclear engine, which will stay in Mars orbit after the lander takes the crew or the cargo to the surface, can produce electricity for orbital functions, including communications with Earth. It will also provide the stage that will return the crew to Earth at the completion of its stay on Mars.

The manned Mars missions that are being developed now are limited by the budgetary constraints that the space agency leadership believes will persist into the future. It is possible, with additional fuel taken to low-Earth-orbit, to trade off some of the cargo on the manned mission in order to decrease the trip time to Mars. For the health and well-being of the crew, this would be the most desirable option.

Tomorrow's Technology Today

Nuclear propulsion is next in the progression of technologies that will enhance the capabilities of mankind in space, and provide the most efficient method for colonizing the Moon. At the same time, moving from chemical to nuclear systems will lay the basis for the quantum jumps in energy technology to follow, most notably thermonuclear fusion.

When discussing the great future city that mankind will build on the Moon, space visionary Krafft Ehricke insisted that "Selenopolis will not be built with yesterday's technology." Thirty years ago, President Kennedy fully expected that the challenges of exploration to follow Apollo would also be based on tomorrow's technology, including nuclear propulsion in space. Today, tomorrow's technologies are well within our grasp.

Marsha Freeman is an associate editor of 21st Century Science & Technology *and the author of* How We Got to the Moon: The Story of the German Space Pioneers, *published by 21st Century Science Associates.*

Notes

1. See Marsha Freeman, "Krafft Ehricke's Moon: A Lush Oasis of Life," *21st Century*, Summer 1998, p. 24.
2. NASA Technical Memorandum 1998-208834. "Vehicle and Mission Design Options for the Human Exploration of Mars/Phobos Using 'Bimodal' NTR and LANTR Propulsion."